AD A

HMMWV FIELD OPERATION DATA COLLECTION AND ANALYSIS

INTERIM REPORT
TFLRF No. 377

by
Douglas M. Yost
Edwin A. Frame

U.S. Army TARDEC Fuels and Lubricants Research Facility
(SwRI®) Southwest Research Institute®
San Antonio, TX

For
U.S. Army Corps of Engineers
Construction Engineering & Research Laboratory
Champaign, IL

Under Contract to
U.S. Army TARDEC
Petroleum and Water Business Area
Warren, MI

Contract No. DAAE-07-99-C-L053 (WD11)

December 2004

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Approved by:

Edwin C. Owens, Director
U.S. Army TARDEC Fuels and Lubricants
Research Facility (SwRI)

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13. ABSTRACT (Maximum 200 words)

A field activity study for HMMWV vehicle was conducted at Fort Hood, Texas. The subject HMMWV was instrumented to record operational data during training. The activity level data were used to provide appropriate weighting factors for exhaust emission data obtained from a 6.5L engine following an 11-mode ISO 8178 test procedure.

14. SUBJECT TERMS					15. NUMBER OF PAGES 31
Exhaust Emissions	Tactical Vehicle	Diesel Fuel	JP-8	Particulate Matter (PM)	
HMMWV	PAH	6.5L Engine	PAH	ISO 8178	16. PRICE CODE
Data Logging	Ft. Hood, TX	EPA Off-road transient test cycle			

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EXECUTIVE SUMMARY

Emissions from tactical vehicle engines contribute to local and regional particulate matter (PM) air pollution. Emissions from these sources are not well understood, and the U.S. Army requires methods/models to predict PM10 and PM2.5 emissions from these military-unique sources. To develop these methods/models, the mass and chemical speciation of tactical vehicle engine emissions need to be characterized. This information should also be useful in developing a method to determine the Army's contributions to atmospheric PM concentrations at receptor sites of concern.

The objective of this phase of the program was to determine a representative field use operational profile for an Army wheeled vehicle used during training exercises. A HMMWV located at Fort Hood; Texas was made available for collection of field operational data. The operational data were collected and analyzed to provide exhaust emissions weighting factors for a series of steady-state speed and load points (see the ISO 8178 11-mode test procedure).

FOREWARD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period February 2003 through December 2004 under Contract No. DAAE-07-99-C-L053. The work was funded by the U.S. Army Corps of Engineers, Construction Engineering Research laboratory (CERL), Champaign, Illinois. The U.S. Army Tank-Automotive RD&E Center, Petroleum and Water Business Area, Warren, Michigan administered the project. Mr. Luis Villahermosa (AMSTA-RBFF) served as the TARDEC contracting officer's technical representative. Mr. Mike Kemme served as the project technical monitor.

The authors would also like to acknowledge the assistance provided by Mr. Robert L. Kennedy of the Directorate of Public Works, Environmental Division at Fort Hood, Texas, Captain Mark Kolvacik of the 21CAV Air Brigade, Ms. Kathy Hillis and the other Dyncorp support personnel from building 6423. The authors also acknowledge the administrative and report-processing support by Ms. Linda De Salme.

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SYMBOLS AND ABBREVIATIONS

AOAP	Army Oil Analysis Program
DF-2	Diesel Fuel
EPA	Environmental Protection Agency
FTP	Federal Test Procedure
G/bhp-hr	Grams/Brake Horsepower-hour
GM	General Motors
HMMWV	High-Mobility Multipurpose Wheeled Vehicle
hp	Horse Power
ISO	International Standards Organization
JP-8	Jet Propellant-8
km/hr	Kilometers/Hour
mg/l	Milligram/Liter
MPH	Miles per Hour
NRTC	Nonroad Transient Test Cycle
PM	Particulate Matter
ppm	Parts per Million
OEM	Original Equipment Manufacturer
OPFOR	Opposing Force
RPM	Revolution per Minute
SAE	Society of Automotive Engineers
SOF	Soluble Organic Fraction
SwRI	Southwest Research Institute®
Tamb	Temperature Ambient
Toil	Temperature of Oil
TARDEC	U.S. Army Tank-automotive RD & E Center
TACOM	Tank-Automotive Armaments Command
TFLRF	U.S. Army TARDEC Fuels and Lubricants Research Facility
vol%	Volume Percent

1.0 INTRODUCTION and OBJECTIVE

Emissions from tactical vehicle engines contribute to local and regional particulate matter (PM) air pollution. The emissions from these sources are not well understood and the Army requires methods/models to predict PM10 and PM2.5 emissions from these military-unique sources. To develop these methods/models, the mass and chemical speciation of tactical vehicle engine emissions need to be characterized. The characterization of these emissions may also be useful in a method to determine the Army's contribution to atmospheric PM concentrations at receptor sites of concern. The establishment of an Army-unique PM source is the first step in the development of a receptor-model-based method that can apportion the PM contribution from all sources, including the Army's.

Part of the Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC/CERL) research program is dedicated to developing the tactical engine emissions information and technology described in the paragraph above.

2.0 HMMWV FIELD ACTIVITY STUDY

A field activity study for a HMMWV vehicle was conducted at Ft. Hood, TX. The subject HMMWV was instrumented to record operational data during training. The activity level data will be used to provide appropriate weighting factors for the 11-mode ISO 8178 (Ref-1) exhaust emission data obtained in a previous program (Ref-2).

2.1 Vehicle Selection and Project Coordination

The SwRI staff arrived at Ft. Hood, building 703, motor pool to instrument HMMWV HHT-6 of the 21CAV air brigade. The vehicle had been inadvertently dispatched till 1400. The dispatcher Ms. Kathy Hillis suggested HHT-6 would have been a poor vehicle for mileage accumulation, since its mission was aircraft recovery. Ms. Hillis suggested contacting the 21CAV OPFOR troop commander Cpt. Mark Kolvacik, as the OPFOR vehicles were highly utilized during training exercises. Ms. Hillis should be acknowledged for her professionalism and help in arranging for another vehicle on short notice. She provided all points of contact for coordinating the vehicle use

and AOAP data for the chosen vehicle. The vehicle chosen has seen 551 miles since the last oil change and 1034-miles since engine overhaul. Cpt. Mark Kolvacik should be acknowledged for allowing us to use OPFOR-6 (VADER-6) for the field testing, his command vehicle, on such short notice before a major training exercise. The building 6423 support contractor employees of Dyncorp were extremely helpful and accommodating.

The HMMWV was scheduled for field exercises from September 28 through October 10, then again from 19-31 October 2003. Figure 1 shows an OPFOR HMMWV with unique panels.

Figure 1. 21CAV Air Brigate OPFOR HMMWV

2.2 Data Acquisition

The engine installed in OPFOR-6 had a tachometer drive that did not work with the Campbell Scientific Model 21X datalogger. SwRI installed the tachometer drive off a 6.5L engine, shown in Figures 2 & 3, which worked with the datalogger.

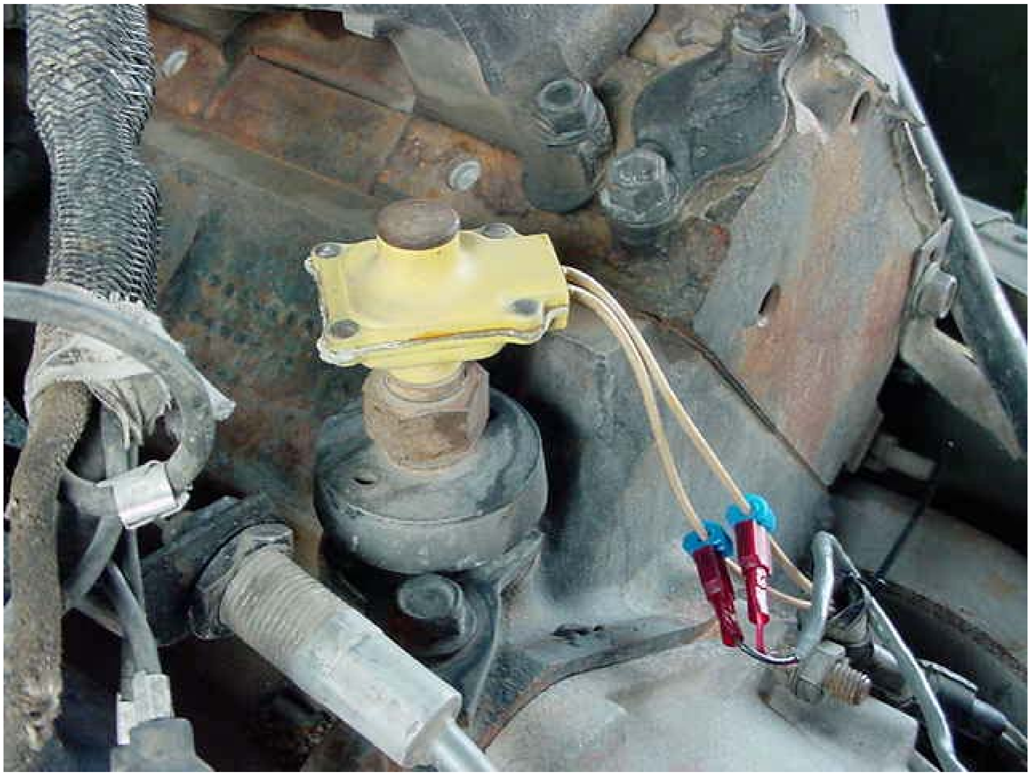

Figure 2. OEM Tachometer Drive

Figure 3. Installed Tachometer Drive

An axle speed sensor was installed on the left rear wheel hub as shown in Figure 4. A bracket assembly was mounted on the hub, and a magnetic pickup was installed and Loctite used on the threads after positioning. Two rare earth magnets were set with epoxy at 180-degree intervals on the CV joint. The axle speed signal was adjusted to correspond to the vehicle speedometer reading.

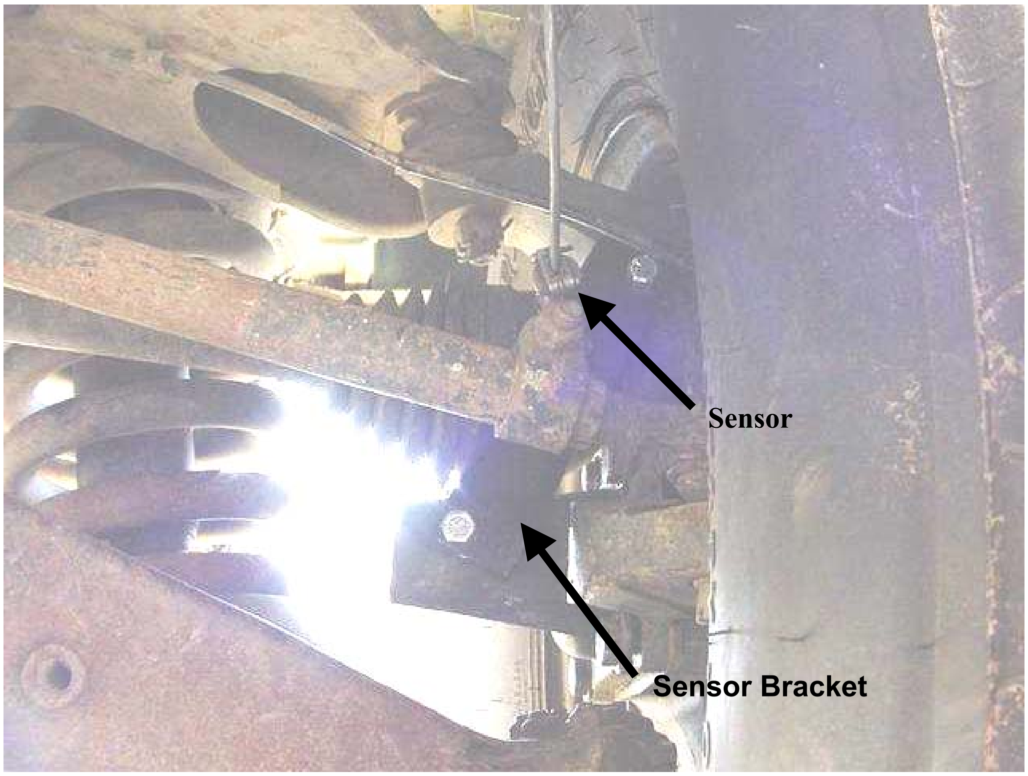

Figure 4. Axle Speed Sensor

A thermocouple was inserted into an oil gallery on the left rear of the engine, just below the oil pressure sensor, and above the lines that go to the oil cooler. The oil temperature thermocouple location is shown in Figure 5. An ambient temperature thermocouple was placed behind the left rear passenger seat. The rack position sensor was attached via a linkage to the accelerator pedal and mounted to the transmission tunnel. The rack position sensor and linkage is shown in Figure 6. The rack position sensor channel on the datalogger was adjusted to read 0% at closed rack and 100% at full rack. The datalogger was installed on the left rear fender, behind the passenger. The position of the datalogger installation shown in Figure 7 was suggested by Cpt. Kolvacik to minimize crew impact during the exercise. Figure 8 shows all the sensor traces after the datalogger

channel constants were set and the vehicle was then operated around the Fort Hood airfield perimeter roads.

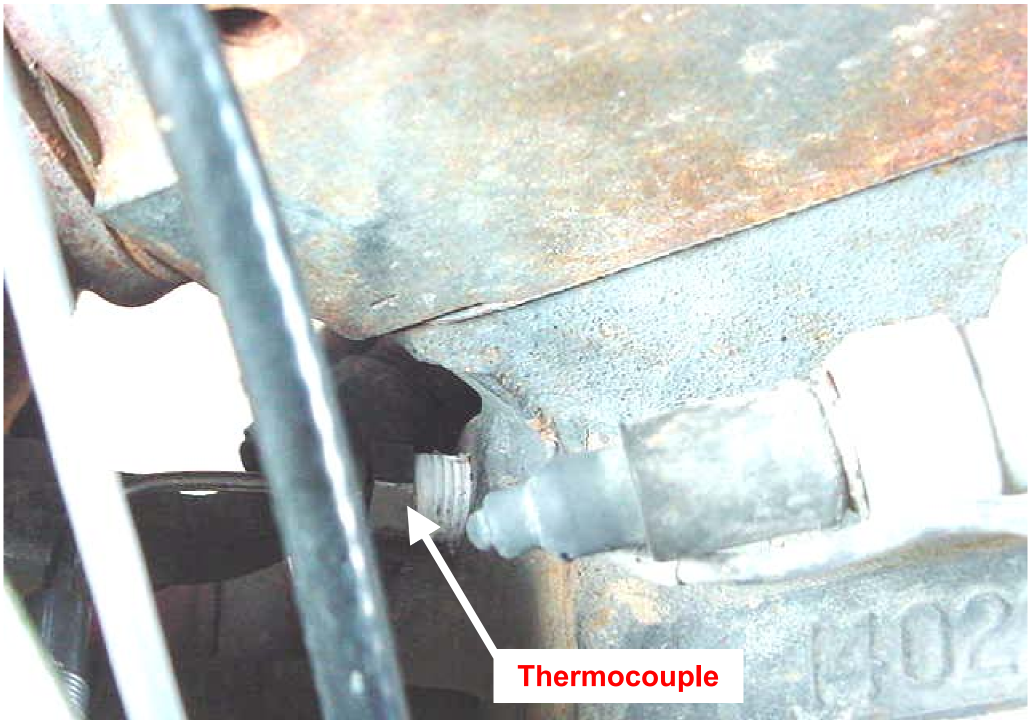

Figure 5. Oil Temperature Thermocouple

Figure 6. Throttle Position Sensor and Linkage

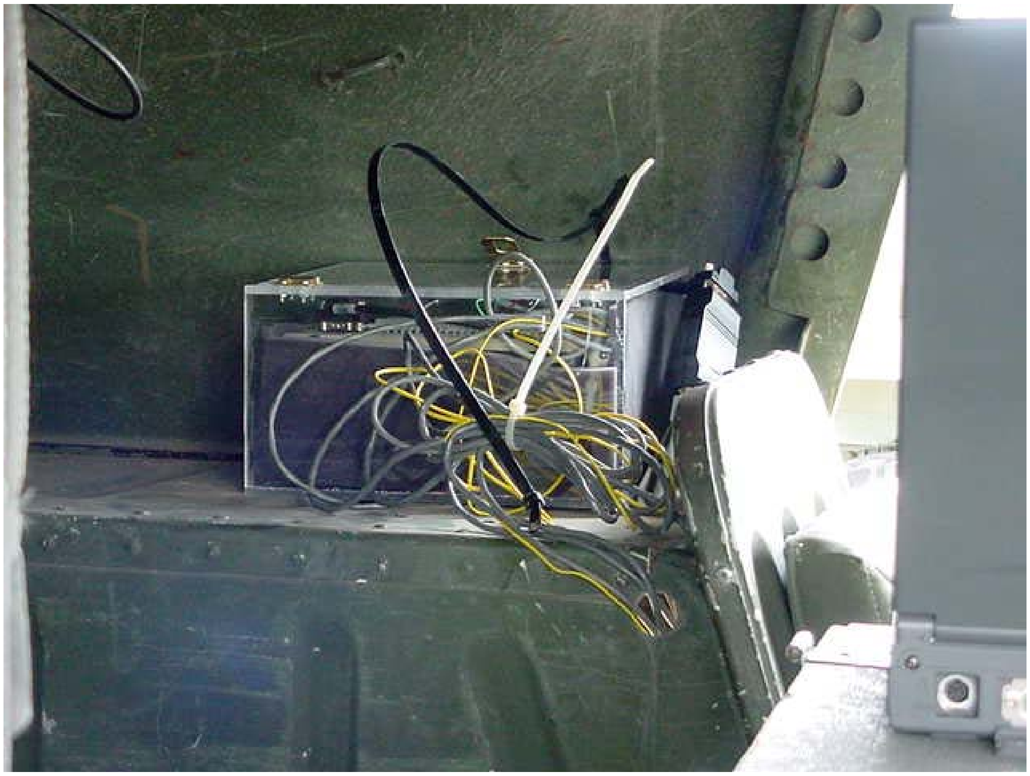

Figure 7. Data Acquisition System Mounted on Left Rear Wheel Well

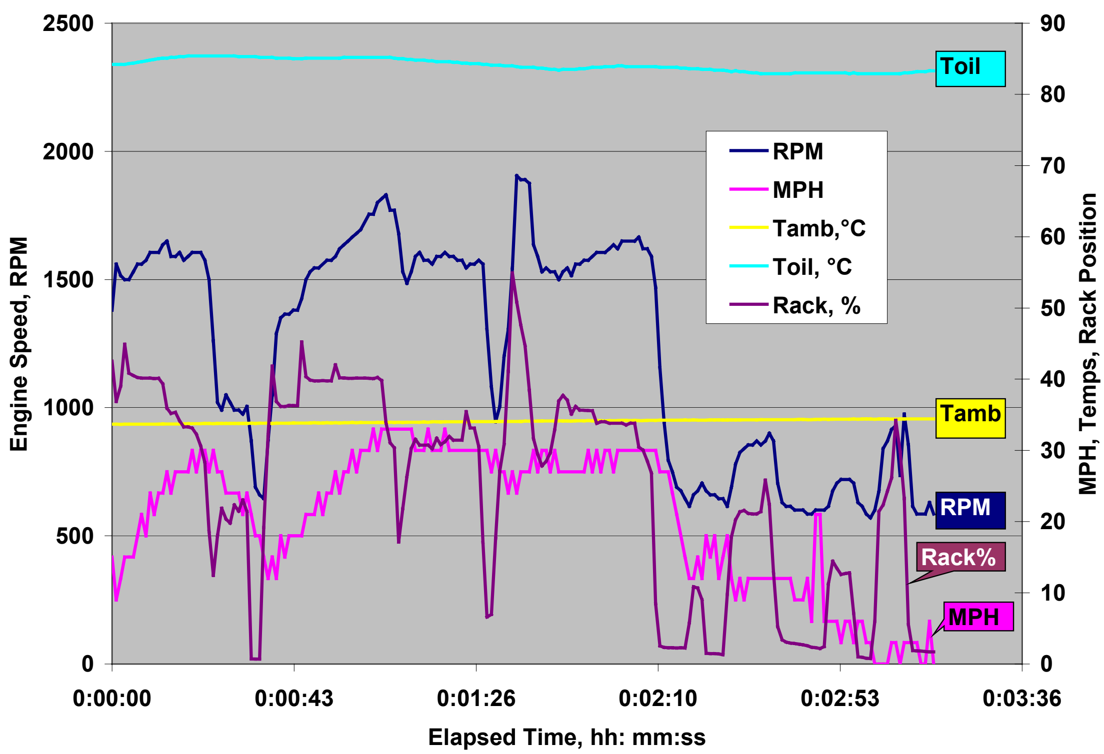

Figure 8. Sensor Traces During Test Run

The OPFOR HMMWVs, Figure 9, were scheduled to return October 10, 2003 and the datalogger storage module was scheduled for removal on October14. A second storage module was to be put on the vehicle at that time for the second two-week field exercise.

Figure 9. OPFOR HMMWVs

The instrumented HMMWV performed the scheduled field exercises from September 28 through October 10, 2003. On October 14, SwRI tracked the HMMWV down at the wash rack and checked the instrumentation. The data storage module did not appear to be saving data, which indicated the engine RPM signal may have been compromised.

When the vehicle returned to building 6423, inspection revealed data had been stored. The 1.6-Mb of usage data was downloaded from the storage module to a laptop. A cursory inspection revealed the RPM sensor had quit working on the morning of October 14. An inspection of the sensor revealed a loose pin in the connector, which was repairable on site. The loose pin indicates some of the data that had been collected may be intermittent because the datalogger code is set up to store

data only when the engine speed is above 60 RPM. The complete data set will be evaluated in the laboratory. All other sensors were functioning properly.

A second storage module was installed on the vehicle for the second two-week field exercise that was scheduled to last from 19 October through 31 October.

The HMMWV performed the scheduled field exercises from October 19 through October 31. When the vehicle was returned to building 6423, inspection on November 4 revealed 2.6-Mb of usage data had been stored. The vehicle OPFOR-6 had accumulated 1730.7 miles during the two-week training exercise. The data acquisition system and wiring was removed from OPFOR-6, and the vehicle returned to the "as found" condition.

2.3 HMMWV Field Activity Data Analysis

An initial look at the field data suggested that a loose pin in the engine speed sensor connector compromised data from the first set gathered (28 September through 10 October). The loose pin appeared towards the end of the exercise. A rational was developed to discard data and look at data which is representative of vehicle usage. Several days in the first test set had less than two-hours worth of readings, and it is likely the valid readings were not contiguous, but intermittent due to the loose wire.

Data from the second gathered set (19 October through 31 October 2003) reveals electrical interference on the pulse counting channels. The pulse counting channels were the engine speed and axle speed. Fortunately, the interference signals result in signals beyond the realm of possible engine or vehicle operation. A procedure was developed based on maximum engine speed and transmission, differential and final drive gearing to evaluate data against engine/vehicle speed criteria to validate readings. Any engine speed over 4000 RPM or any vehicle speed over 80-mph were discarded. Each data set contains 10-12 days with 11000 to 25000 readings per day of data to evaluate.

A program was written to characterize the field data in a series of bins that corresponded to the power levels calculated for the ISO 8178 11-mode dynamometer cycle. Fortunately, the power levels for all 11-modes, of the ISO 8178 procedure, were unique as shown in Table 1.

Table 1. ISO 8178 Test Modes

Mode	Speed/% torque
1	rated/100
2	rated/75
3	rated/50
4	rated/25
5	rated/10
6	intermediate/100
7	intermediate/75
8	intermediate/50
9	intermediate/25
10	intermediate/10
11	low idle

A full load torque curve on JP-8 was available for a GM 6.2L engine for every 100-rpm starting at idle, up to 3900-rpm (Ref. 2). Engine speed and rack position data for each point from the field trials were used to estimate a power level. Using the acquired engine speed, an interpolation of the available full-rack power curve defined the maximum torque at the acquired speed. The maximum torque available at the acquired speed was adjusted by multiplying by the percent rack position to obtain the road load torque. The estimated road load torque multiplied by the acquired engine speed and the sum divided by 5252.1 was used to obtain the estimated road load power.

Although this approach assigns power values o the field data, it should be cautioned that actual in use power levels are likely influenced by vehicle and engine inertia. These transient effects manifest due to vehicle accelerations or decelerations would also have effect on emissions, notably smoke and particulate matter.

The estimated road load power was then classified in bins according to the ISO 8178 power levels for each test day. The bin counts for each power level were divided by the total counts for the test day to obtain a daily power level weighting factor. The average daily field weights, by two sorting methods, are shown with respect to the ISO 8178 weights for the field trial in Table 2. The first sets of field weights are the percentage of values, which are less than or equal to the ISO Power Bin value. The

+/- field weights are the percentage of values, which are less than or equal to the +/- Power Bin values. The +/- Power Bin values are the average power value between two adjacent ISO power bins (i.e. average 0.2 and 10.2 is 5.2), thus bracketing the actual ISO power value.

The biggest classification impact is on idle power, but for military vehicles, which run high alternator loads at idle to run communications and auxiliaries, the +/- weighting may be more realistic.

Table 2. Average Daily Field Weights for Exercise

ISO 8178 Mode No.	ISO Power Bins	ISO 8178 Weights	Field Weights	+/- Power Bins	+/- Field Weights	NOx gr/hour	PM gr/hour
11	0.2	0.15	0.27	5.2	0.35	21	3.18
10	10.2	0.00	0.12	11.85	0.05	55	10.29
5	13.5	0.10	0.03	18.9	0.06	127	12.39
9	24.3	0.00	0.10	29.95	0.10	96	7.48
4	35.6	0.00	0.11	43.15	0.13	176	8.94
8	50.7	0.10	0.15	59.65	0.16	159	5.11
3	68.6	0.15	0.14	72.2	0.07	241	6.49
7	75.8	0.10	0.03	88.8	0.04	176	4.86
2	101.8	0.15	0.05	102	0.02	314	5.19
6	102.2	0.10	0.00	118.45	0.01	194	8.35
1	134.7	0.15	0.01	134.7	0.00	339	6.09

The bin classifications are assigned an emission value based upon the mass emission rate for a power level from ISO 8178 testing. The bin classifications are then multiplied by a bin weight to obtain a weighted average emission. Figure 10 shows how the ISO emission results are applied to the categories determined utilizing the straight Field Weights or the +/- Field Weights. In Figure 10, the solid boxes and colors highlight the Field Weight range of values that are assigned a specific emission rate. For example, the percentage of total readings counted in the light blue region are assigned the emission value for 0.2-BHP, likewise for the purple, red etc. regions of operation. Also in Figure 10 the crosshatched boxes and colors highlight the +/-Field Weight range of values that are assigned a specific emission rate. For example, the percentage of total readings counted in the

light blue crosshatched region (values greater than 0 and less than 5.2-BHP) are assigned the emission value for 0.2-BHP.

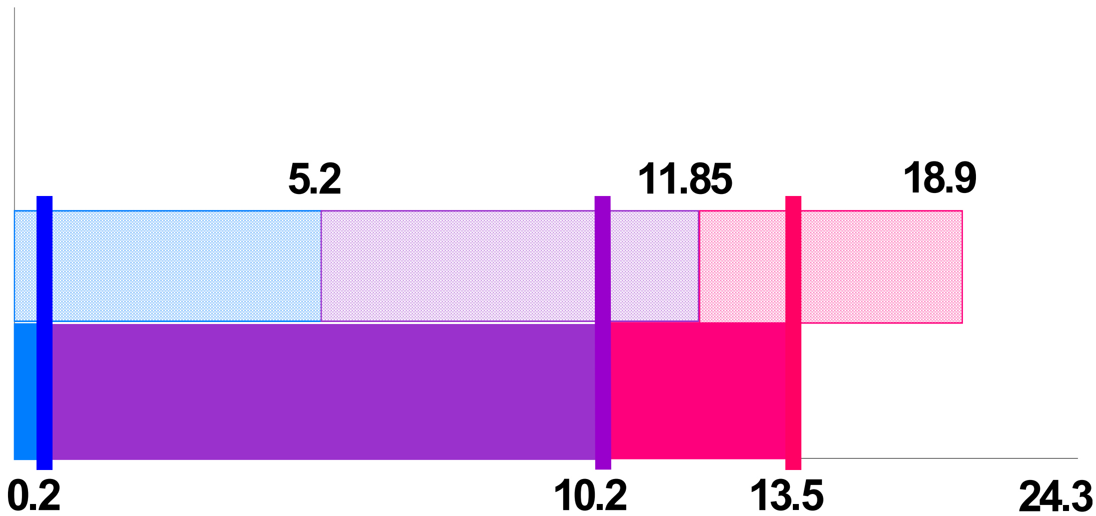

Figure 10. Weighting Schemes for Application of ISO 8178 Emission Rates to Field Data.

Utilizing weights calculated from the field data and adjusted by ISO 8178 emission rates for JP-8 fuel, the predicted specific weighted emissions for the combined field exercises are shown in Figures 12-14.

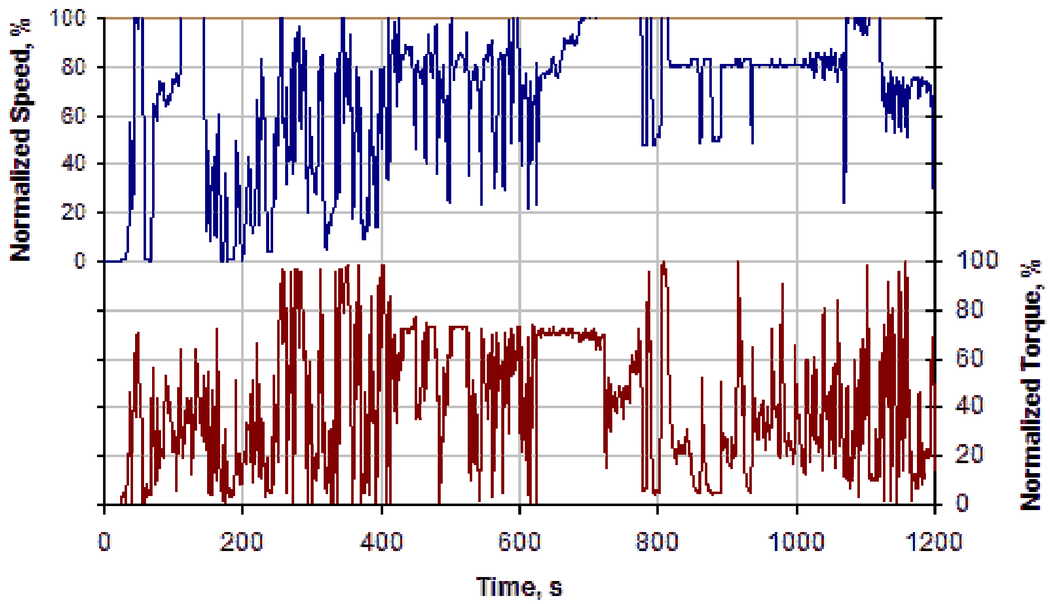

Figure 11. Proposed EPA Non-Road Transient Test Command Cycles

The EPA non-road transient dynamometer command cycles for speeds and loads are shown in Figure 11. During the transient test the gaseous emissions are collected in a bag and the particulate emissions are collected on a filter for the duration of the test. Post test, the emitted concentrations are determined in the bag, and the particulate filters are weighed. With proper measurement of fuel and air used by the engine, the mass emissions are calculated. Likewise the power can be integrated over the cycle to calculate a cycle average power. The results shown in Figures 12-14 for EPA are the integrated results from the transient dynamometer tests for the GM6.5L engine.

The same program used for analyzing and classifying the HMMWV field data processed a file containing the second-by-second speed and torque commands for the EPA non-road transient cycle. The normalized torque command was treated as percent rack for the peak torque available at the command speed for the same time step. Using the engine dynamometer torque curves and the ISO 8178 steady-state emission results, the EPA non-road transient test cycle was classified in bins represented by the ISO 8178 power levels and the emissions calculated. The EPA non-road transient cycle was evaluated in terms of both categorization procedures discussed previously, EPA bin weighted and EPA mid weighted as shown in Figures 12-14.

Figure 12 shows the weighted average power determined for the ISO 8178 testing, the field testing, and the weighted EPA test cycle. The EPA transient testing value is the integrated average power of the test cycle. The certification tests are performed at power levels greater than those the vehicle experiences during the field exercises. The EPA off-road transient test cycle operates at a power level closer to actual Army operation.

Figure 13 shows the weighted average brake specific NOx emissions determined for the ISO 8178 testing, the field testing, the EPA transient testing, and the weighted EPA test cycle. The brake specific emission is calculated by the weighted average of the NOx emission rate divided by the weighted average power. The greater certification test power levels are reflected in the brake specific NOx calculation. The EPA off-transient test cycle NOx more closely represents the NOx from actual Army operation.

Figure 14 shows the weighted average brake specific PM emissions determined for the ISO 8178 testing, the field testing, the EPA transient testing, and the weighted EPA test cycle. The brake

specific emission is calculated by the weighted average of the PM emission rate divided by the weighted average power. The brake specific PM calculation is sensitive to the low power levels that were seen during the field testing. The field testing showed a large increase in weighting factor at the idle and low power conditions. The EPA transient test PM under-predicts the PM from actual Army operation based on the steady-state ISO weights. This result was not expected because transient tests usually have higher PM due to the acceleration events.

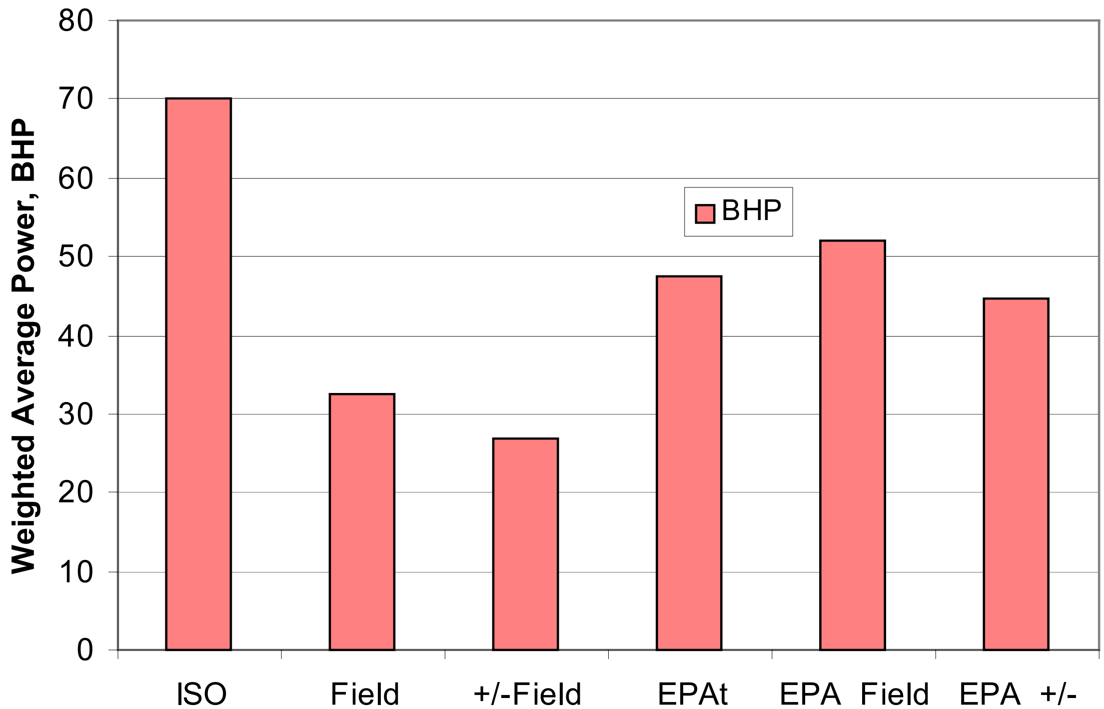

Figure 12. Power Levels

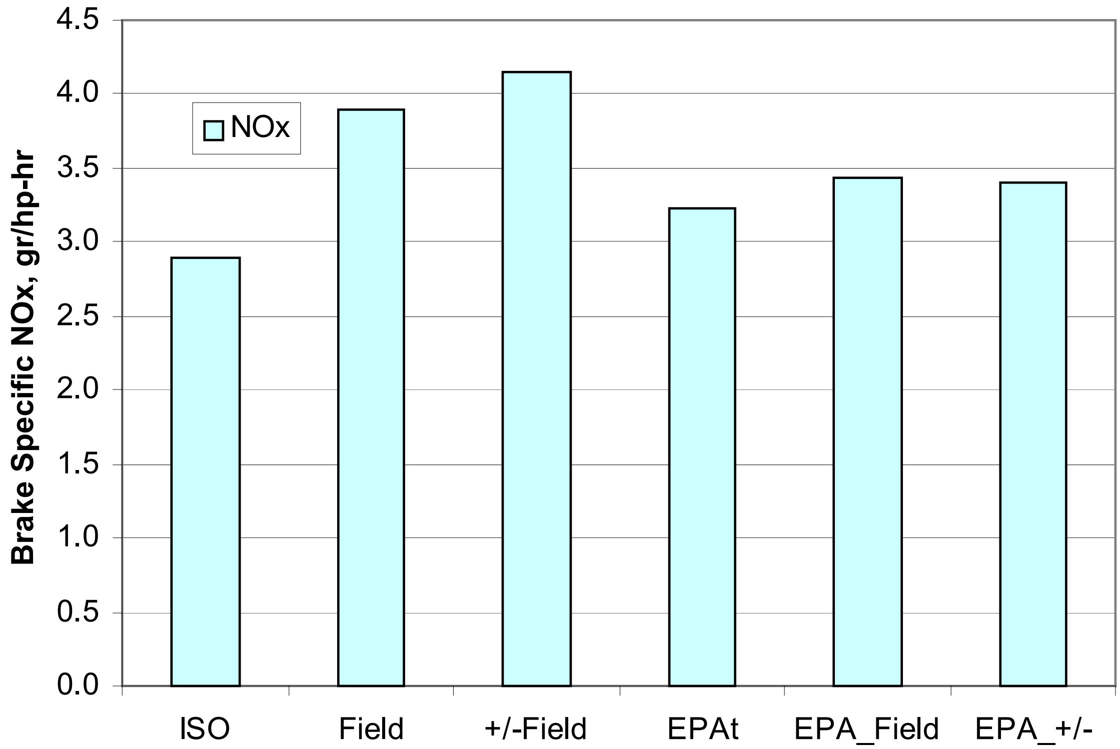

Figure 13. Weighted NOx Emissions

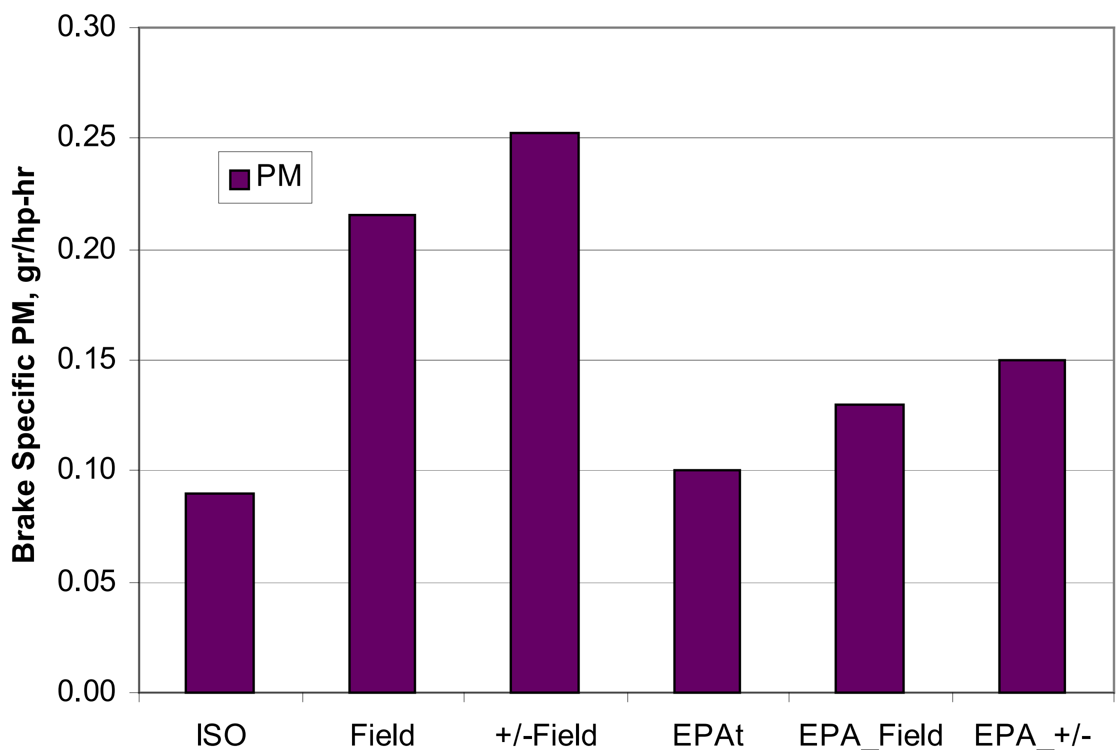

Figure 14. Brake-Specific Weighted PM Emissions

3.0 CONCLUSIONS

Field operational data were collected for a HMMWV during training exercises at Ft Hood, TX. The data were analyzed and a set of field weighting factors ere developed for the ISO 8178 11-mode steady-state test procedure. The field weighting factors were based on observed field power levels as they related to the power levels of the ISO-8178 procedure. See Table 3 for the field weightings that were developed for the 11-modes:

Table 3. Field Weighting

ISO 8178 Mode Number	Recommended Field Weighting
1	0.00
2	0.01
3	0.08
4	0.15
5	0.07
6	0.00
7	0.04
8	0.19
9	0.13
10	0.06
11	0.27

These field weightings can be applied to ISO 8178 11-mode exhaust emission data to get an estimate of US Army field training exhaust emissions.

4.0 RECOMMENDATIONS

1. HMMWV field exhaust emissions can be estimated from the data collected in this study. Additional data collection of HMMWV usage would better define “typical Army use patterns” for this class of vehicle.

2. Field operational data should be collected from other instrumented Army ground vehicles to determine their respective contributions to emission levels at Army facilities.

5.0 REFERENCES

1. ISO 8178, EPA Federal Test Procedure (FTP) as specified in the Code of Federal Regulations (CFR), Title 40, Part 89, Subpart E, entitled "Control of Emissions from New and In-use Nonroad Compression Ignition Engines: Exhaust Emission Test Procedures."

2. Frame, E. A., and Blanks, M. G., " Emissions From a 6.5L HMMWV Engine on Low Sulfur Diesel Fuel and JP-8", Interim Report Number TFLRF-376, December 2004.

APPENDIX A

DAILY WEIGHTED RESULTS

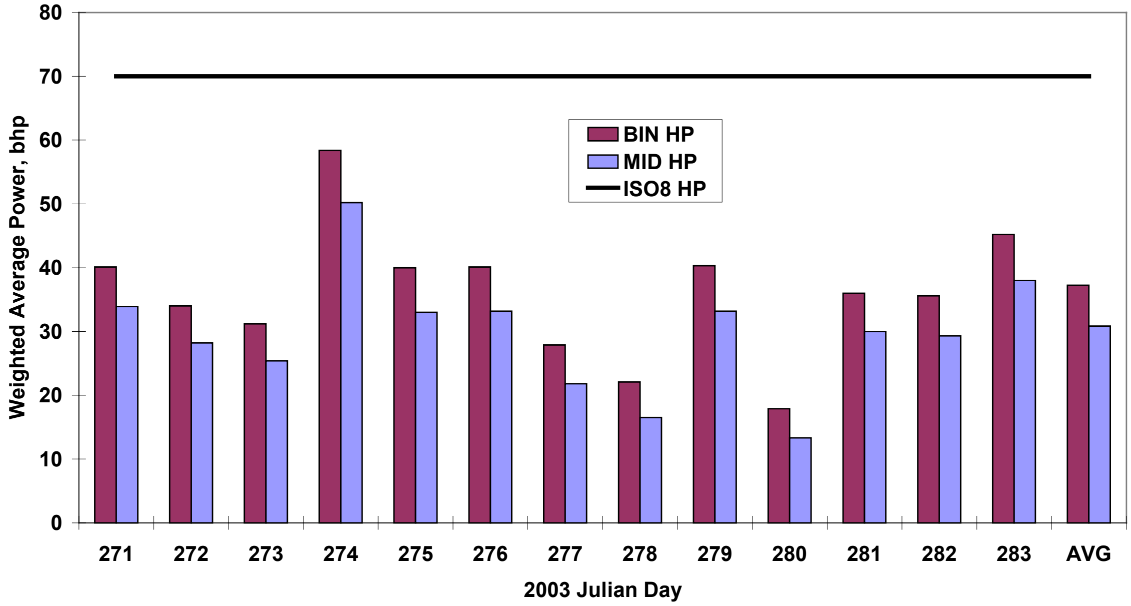

Figure A1. Weighted Average Power

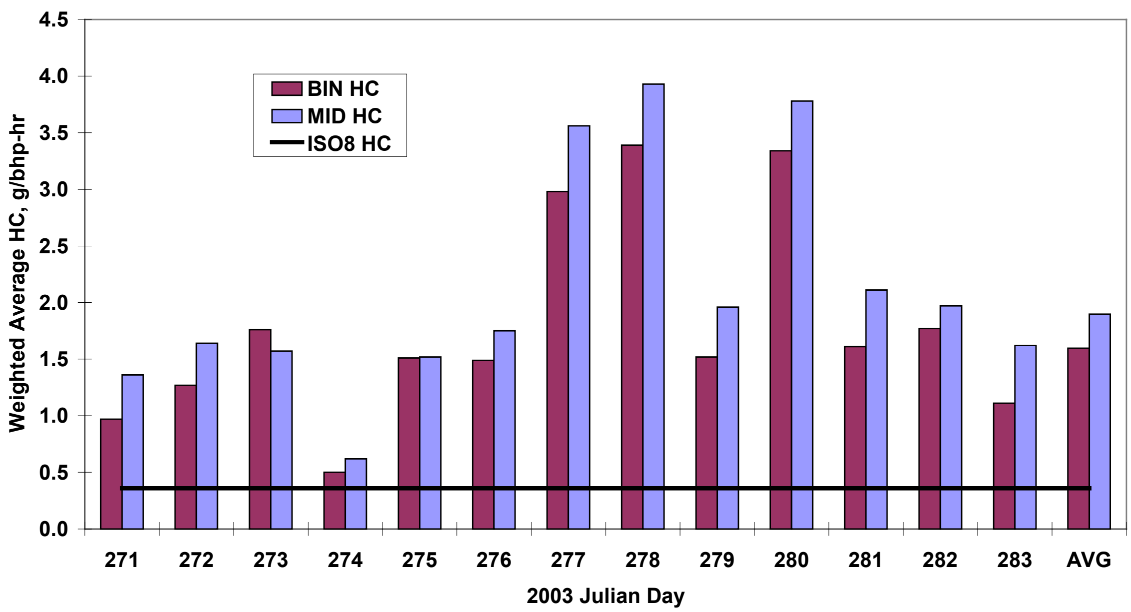

Figure A2. Weighted Average HC

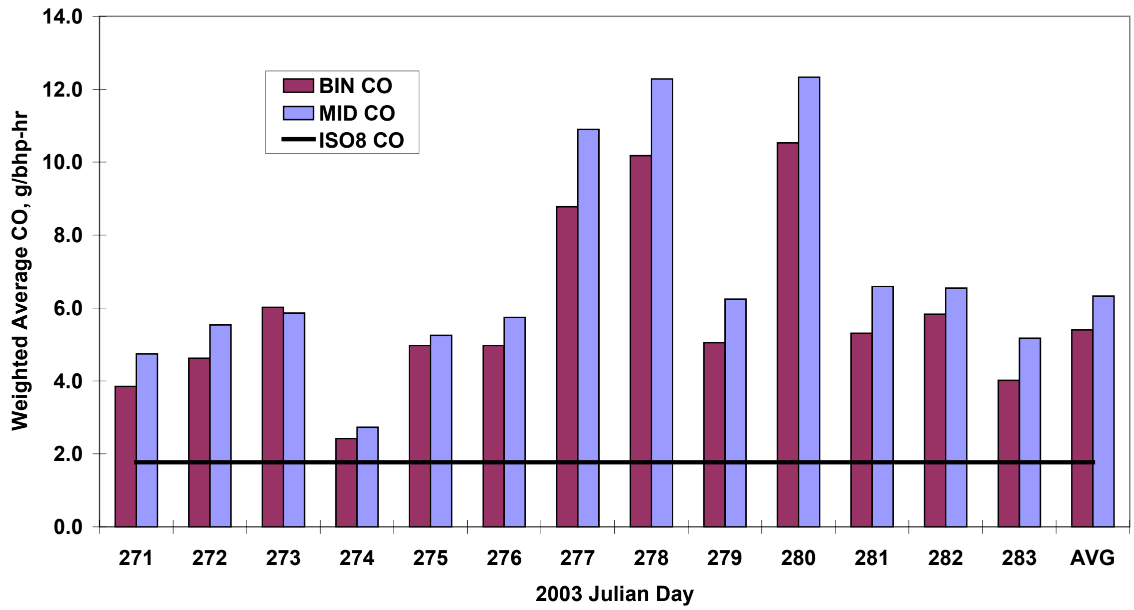

Figure A3. Weighted Average CO

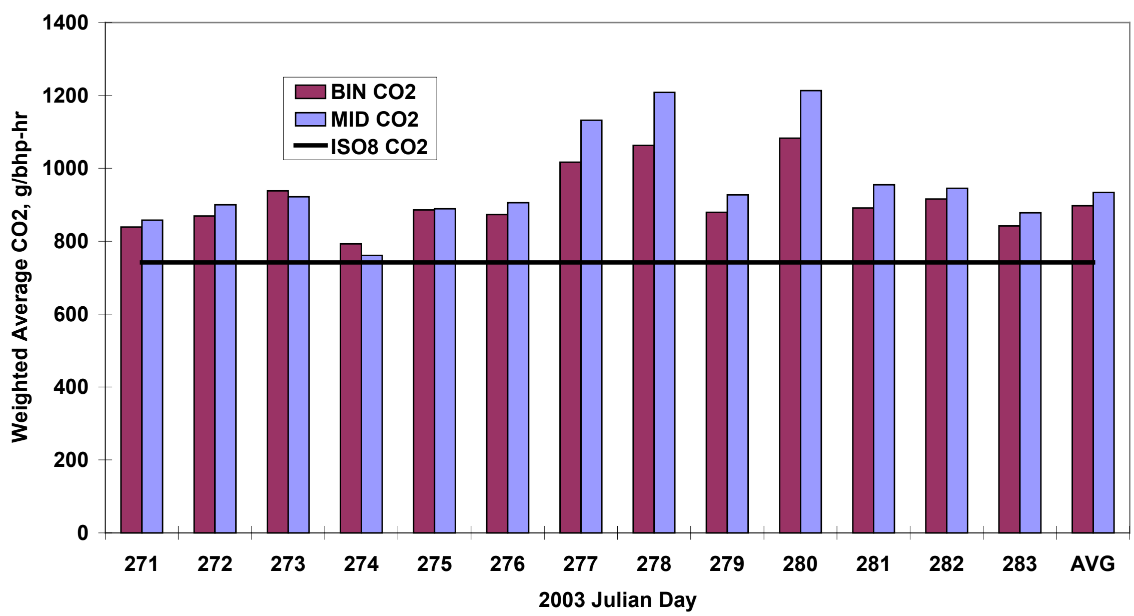

Figure A4. Weighted Average CO_2

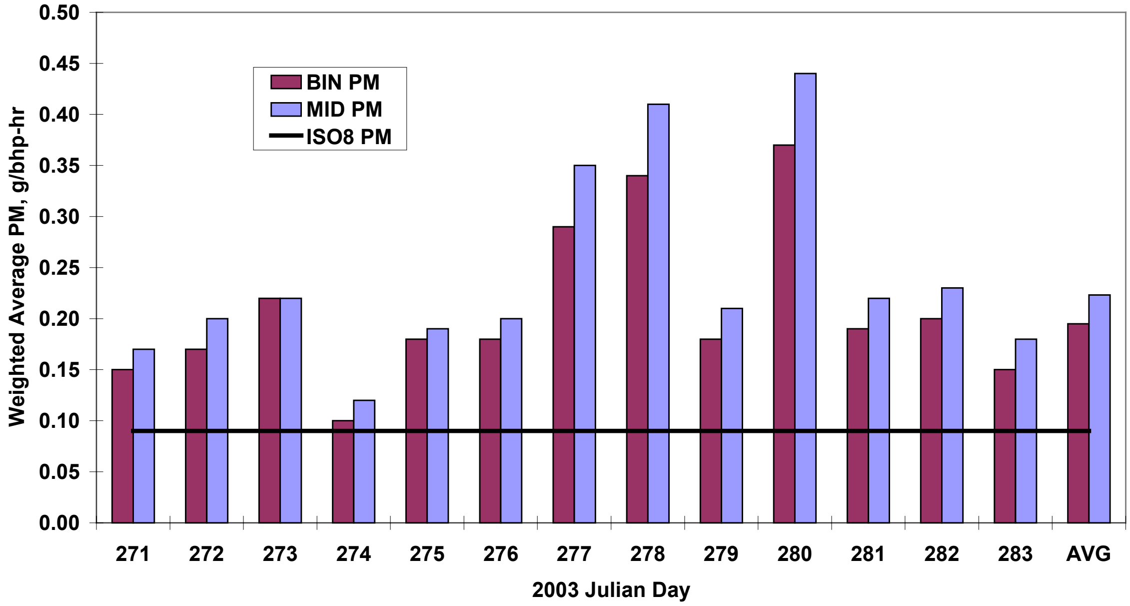

Figure A5. Weighted Average PM

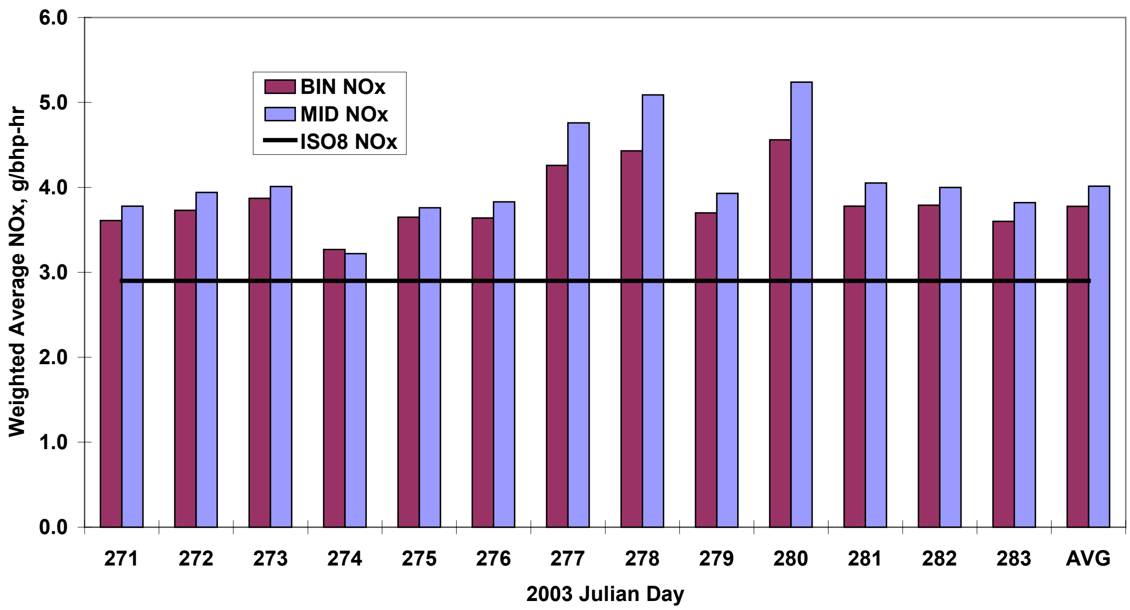

Figure A6. Weighted Average NOx

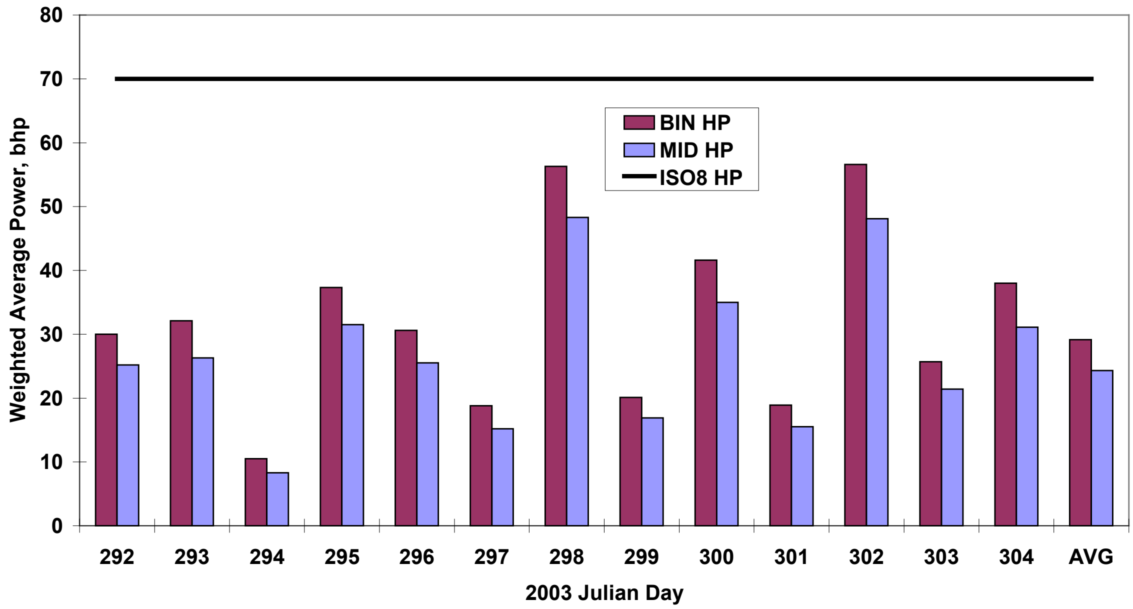

Figure A7. Weighted Average Power

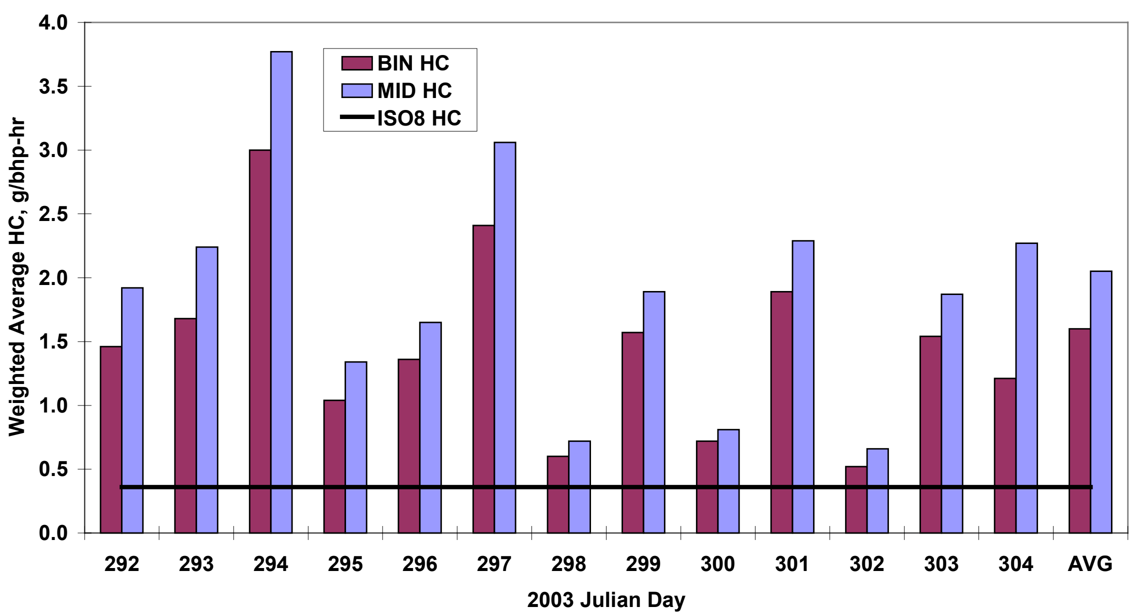

Figure A8. Weighted Average HC

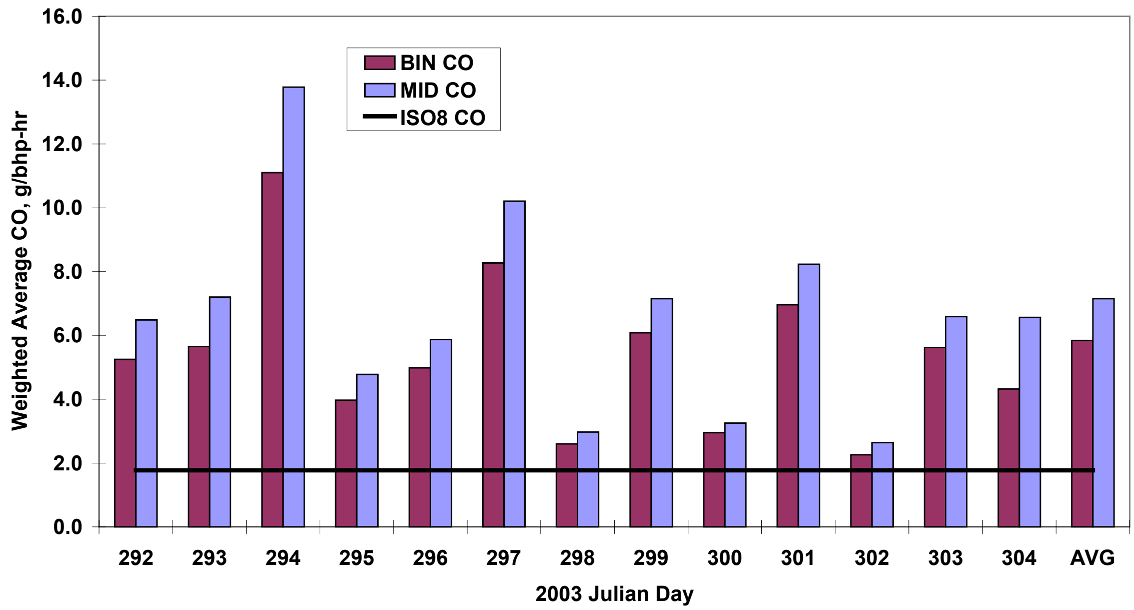

Figure A9. Weighted Average CO

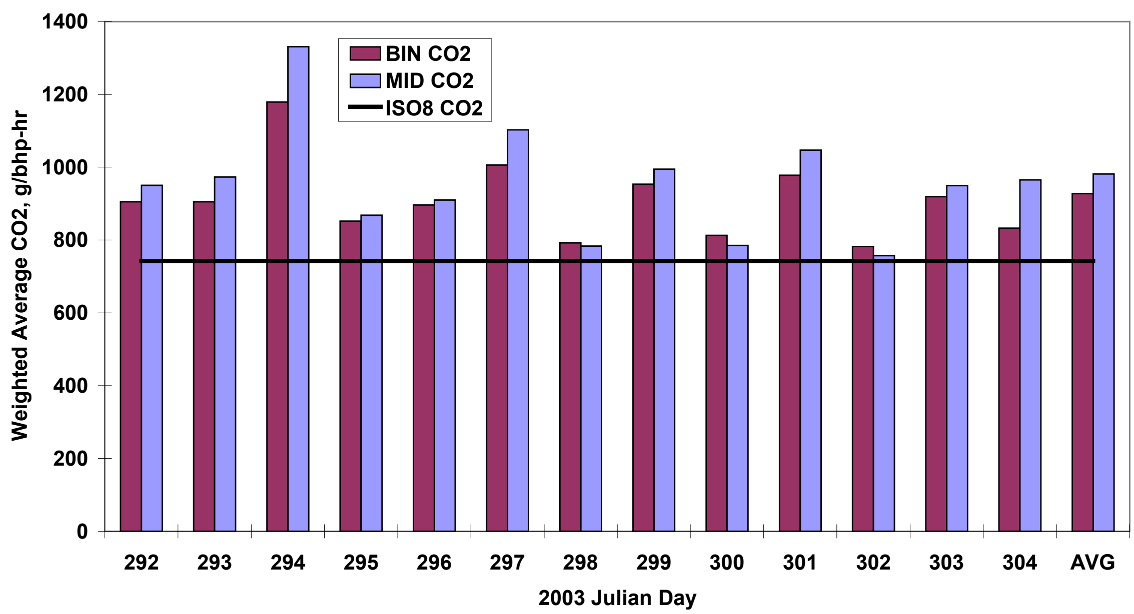

Figure A10. Weighted Average CO_2

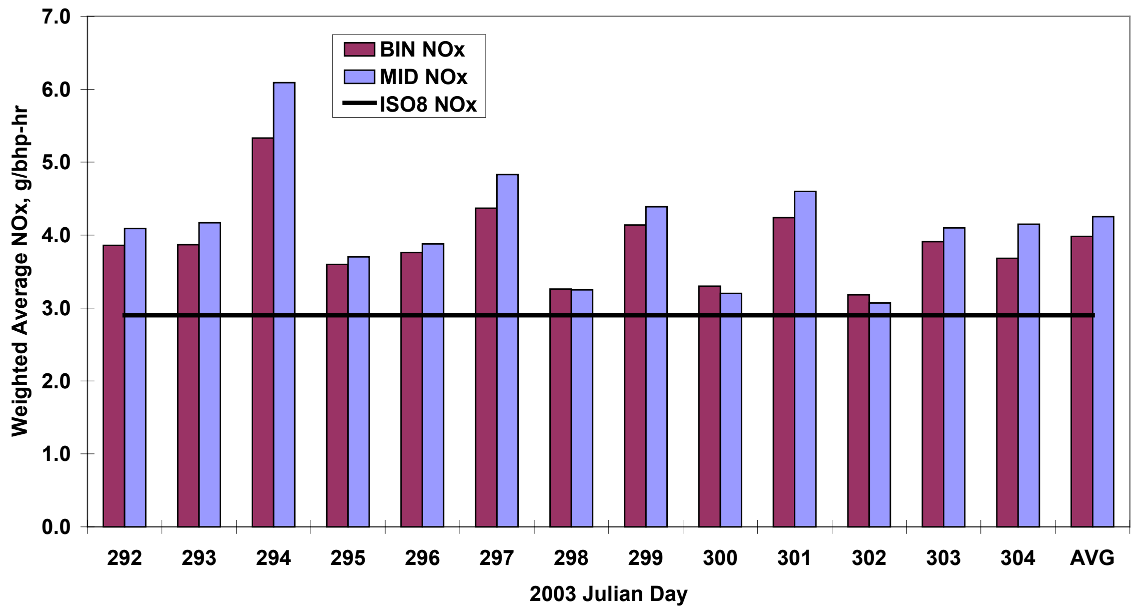

Figure A11. Weighted Average NOx

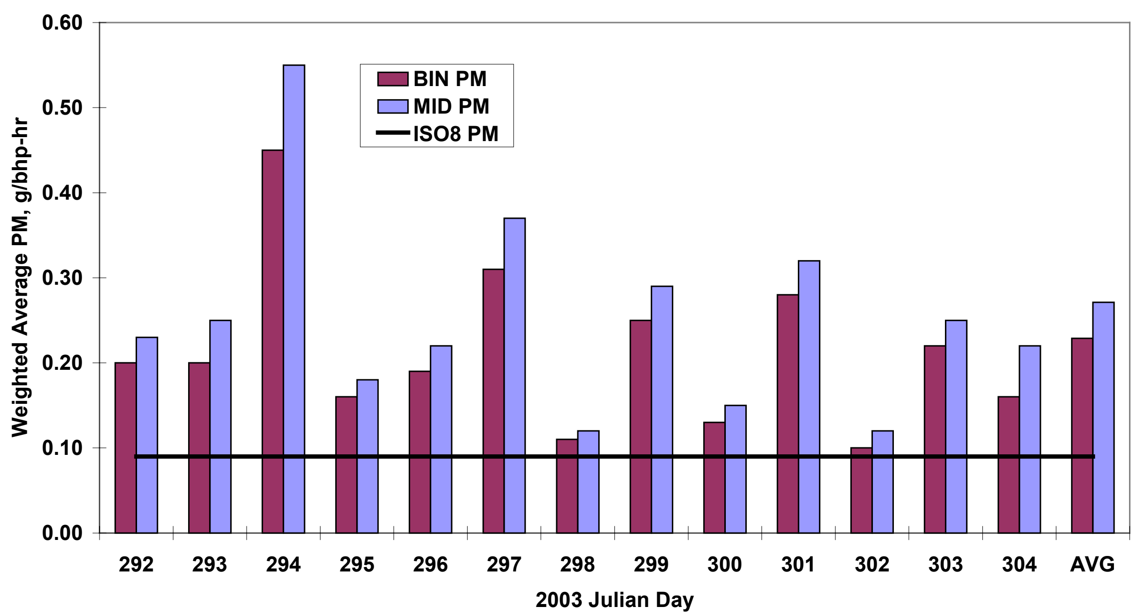

Figure A12. Weighted Average PM